Appendix C

Update of Nitrate Plume Simulation in the Snake River Plain Aquifer from Operation of the CFA-08 Sewage Treatment Plant Drainfield, 1953-1995

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C1. INTRODUCTION

The Central Facilities Area (CFA)-08 sewage treatment plant and drainfield operated between 1953 and 1995. The drainfield received effluent from the laundry and other CFA facilities. Beginning in 1995, CFA-08 was taken offline and replaced with a new sewage treatment plant, complete with center-pivot irrigation and a sewage lagoon. Three monitoring wells (CFA-MON-A-001, -002, and -003) were installed in 1996 to monitor effluent in the Snake River Plain Aquifer (SWA) from the new sewage treatment plant.

Nitrate was detected immediately in water samples taken from these newly installed wells. Nitrate concentrations in CFA-MON-A-002 exceeded the maximum contaminant level of 10 mg/L. Based on travel times, however, the new sewage treatment facility was an improbable source of the nitrate detected. Informally, these wells were included in the Operable Unit (OU) 4-12 landfill-monitoring program.

Because the $\delta^{15}N$ value of the nitrate in the CFA-MON wells was a couple per mil higher than background, the nitrogen isotopic analysis suggested that the nitrate was derived from sewage sources rather than from commercial sources, such as nitric acid disposed into the CFA-04 dry pond. Therefore, these calculations were requested to (a) determine the likelihood that CFA-08 was the source of the nitrate detected in the monitoring wells and (b) determine how the plume is currently delineated in the aquifer and how long is it expected to persist, assuming CFA-08 was the source of the nitrate.

This appendix is an update of an initial simulation of the nitrate migration from the CFA-08 drainfield (INEEL 2002), incorporating new models, data, and other pertinent information.

C2. CONCEPTUAL MODEL AND ASSUMPTIONS

The original nitrate simulation used the pond model described in GWSCREEN Version 2.5 (Rood 1999). The conceptual model implemented in GWSCREEN for an infiltration pond considers a rectangular percolation pond where liquid effluent is discharged at a constant rate over the period of operation. Moisture content and water flow rates in the underlying strata are assumed to be at steady state and equal to the water flow rate into the pond. Water movement in the unsaturated zone is assumed to be gravity-driven and in the vertical direction only; no appreciable horizontal movement is assumed. The aquifer is assumed to be a homogeneous isotropic media of infinite lateral extent and finite thickness. Flow is assumed to be unidirectional and at a steady state. There is no water mass balance in GWSCREEN, because it is assumed that the water entering the aquifer from the source is insignificant compared to the flow in the aquifer. For the volumes of water considered in an infiltration pond, this assumption may be violated. Therefore, GWSCREEN Version 2.5a incorporates a dilution factor that accounts for water entering the aquifer from the pond or another source.

The revised calculations reported in this document used the HYDRUS-2D (CSM 1996) code to compute water fluxes and solute concentration to the SWA. HYDRUS-2D is a two-dimensional finite-element-flow and transport model for variably saturated porous media. GWSCREEN was retained for simulation of the nitrate plume in the SWA.

The unsaturated zone underlying the INEEL is composed of massive fractured basalt flows interrupted by relatively thin sedimentary interbeds. Of particular importance is the amount of horizontal spreading that might take place on a sedimentary interbed while the drainfield is operating; also important is the time necessary for the unsaturated zone to dry out after cessation of operations. The stratigraphy of the unsaturated zone was delineated using the lithology log from well CFA-1, which is located about 0.5 km southwest of CFA-08 (Figure C-1).

The drainfield was assumed to represent a square with an area equivalent to the total surface area of the drainfield. The dimensions of the drainfield were reported to be 61 m x 305 m for a total area of 18,605 m^2. The length of one side of the drainfield is then (18,605 m^2)$^{1/2}$ = 136 m. A plane of symmetry is assumed for the left-side boundary condition (no flow); therefore, one-half the length is simulated (68 m).

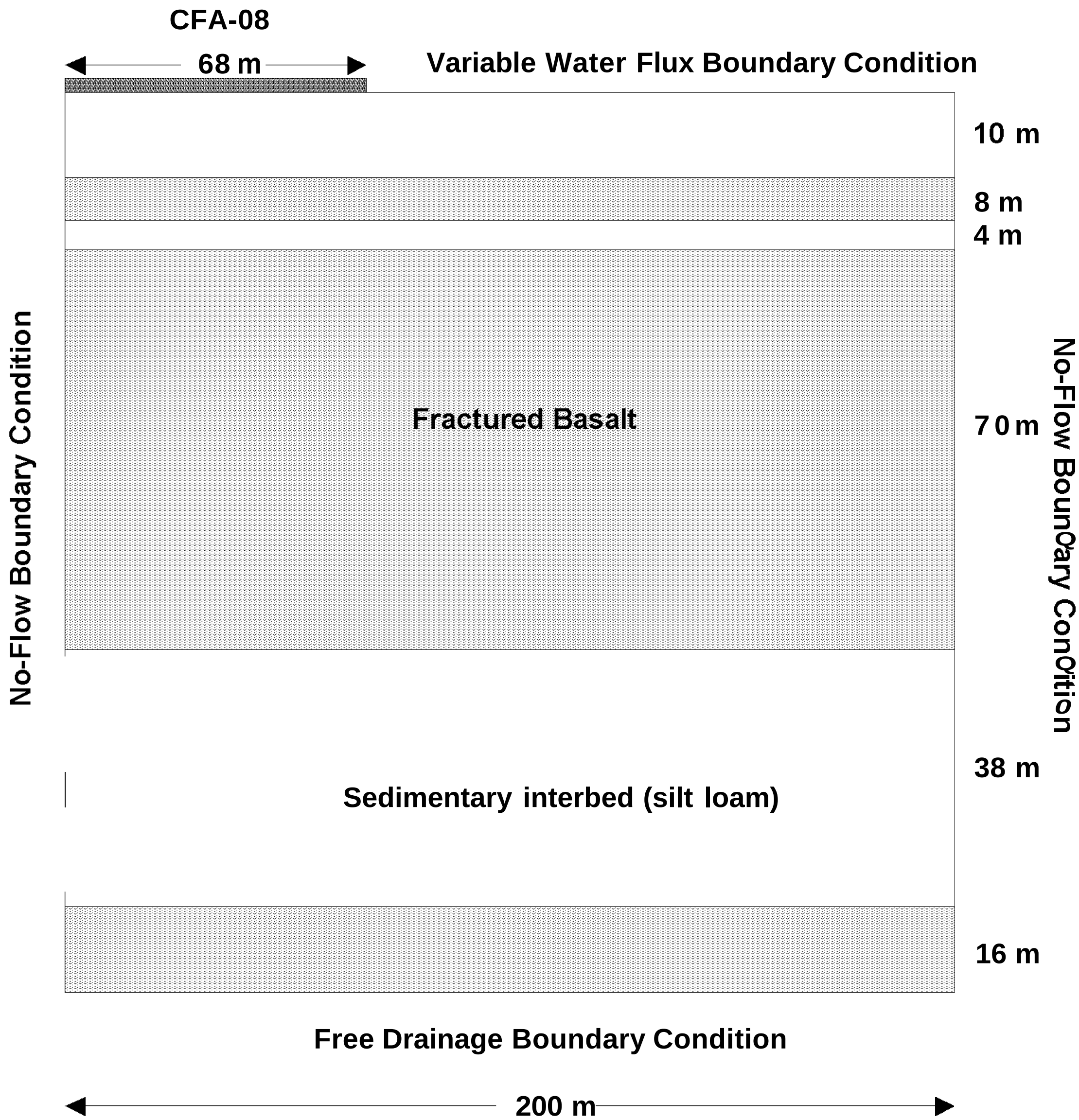

Figure C-1. Model domain and unsaturated zone lithology for the HYDRUS 2D simulation of the CFA-08 drainfield. Lithology of the unsaturated zone was based on well CFA-1, which is located about 0.5 km southwest of CFA-08.

Dissolved-phase nitrate is introduced into the system via the liquid effluent flowing into the drainfield. The nitrate is then transported through the unsaturated zone to the saturated zone. Nitrate discharges are assumed to occur at a constant rate for 42 years (i.e., 1953 to 1995). After 1995, nitrate discharges and water fluxes cease, and the unsaturated zone beneath the drainfield drains and eventually dries out.

Water and nitrate fluxes were computed in HYDRUS and extracted into ASCII files. Solute fluxes were then input to GWSCREEN for estimates of aquifer concentrations at the CFA monitoring wells located downgradient from CFA-08 (see Table C-1 and Figure C-2). Aquifer concentrations in GWSCREEN were corrected for the additional water added to the aquifer from the drainfield.

The original assessment also included data from well USGS-83, which has shown consistently low concentrations of nitrate and other contaminants, including tritium. Arnett et al. (1994) concluded that USGS-83 appears to be an anomaly, because concentrations of tritium in this well show little correlation with tritium concentrations in nearby wells. For this reason, data from this well were ignored.

CFA-MON-A-002		CFA-MON-A-003		CFA-MON-A-001	
Date	Nitrate Concentration (mg/L)	Date	Nitrate Concentration (mg/L)	Date	Nitrate Concentration (mg/L)
07/12/96	20.4	07/12/96	11	07/12/96	1.7
10/17/96	18.8	10/17/96	9.52	10/18/96	1.76
01/06/97	1.95	01/06/97	2.22	01/06/97	2.25
04/16/97	20.5	04/16/97	11	04/16/97	2.14
10/14/97	19.1	10/14/97	10.2	10/14/97	2.18
01/13/98	18	01/13/98	10	01/13/98	1.79
04/08/98	16	04/08/98	11	04/08/98	1.74
05/12/99	19.2	03/15/00	9.6	05/11/99	1.5
03/15/00	16	03/15/00	9.7	06/02/99	1.5
08/16/00	17.8	08/29/00	9.73	09/07/00	1.72
10/17/01	19.8	10/17/01	10.8	10/17/01	1.5
10/01/02	19.8	10/01/02	11	10/01/02	1.62

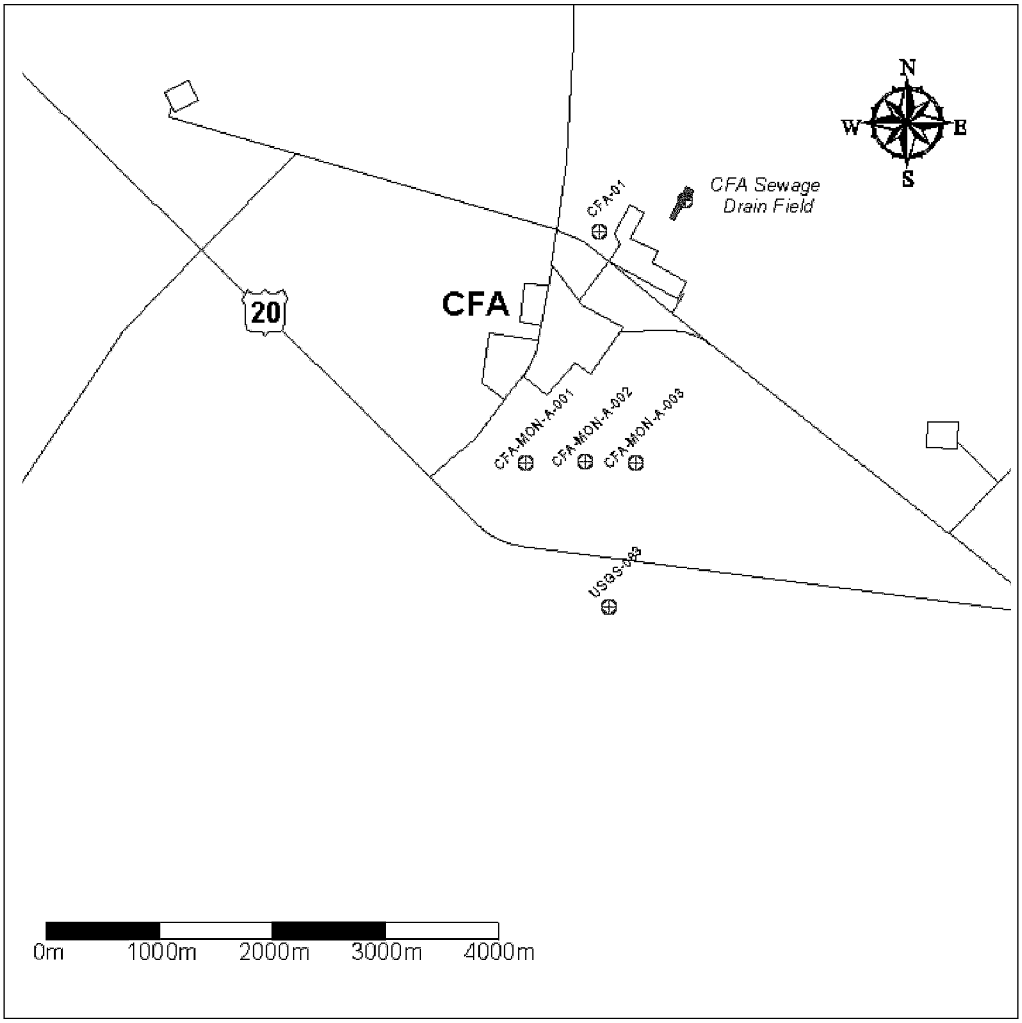

Figure C-2. Location of CFA sewage drainfield (CFA-08), monitoring wells (CFA-MON-A-001 through -003), CFA-01, and well USGS-83. The data from USGS-83 were ignored for reasons explained in the text.

C3. HYDRUS MODEL INPUT

A finite element mesh was constructed using the MESHGEN utility in HYDRUS (see Figure C-3). The mesh was refined near the boundaries of lithologic units. Sedimentary units were represented by a silt-loam soil type (see Table C-2), and the HYDRUS default properties were used for this material type. Properties for the basalt were obtained from Holdren et al. (2002). The thickness of each unit is shown in Figure C-1. The simulation was initialized with the steady-state moisture contents from background infiltration (1 cndyr). Boundary conditions included a no-flow boundary on the left and right sides of the model domain, free drainage at the base, and background infiltration (1 cm/yr) along the top boundary outside the boundaries of the drainfield. The average annual water flux to the drainfield used in the original simulation (Rood 1999) was 260,000 m^3/yr. Dividing this value by the area of the drainfield (260,000 m^3/yr $\div$ 18,605 m^2 = 13.97 m/yr) yields a net infiltration of about 14 m/yr while the drainfield was operating. This water flux was applied to the 68-m length of the simulated drainfield. A unit solute concentration (1 mol/m^3) was assigned to the water entering the drainfield. Solute fluxes at the base of the unsaturated zone could then be scaled according to the actual nitrate concentration in the effluent.

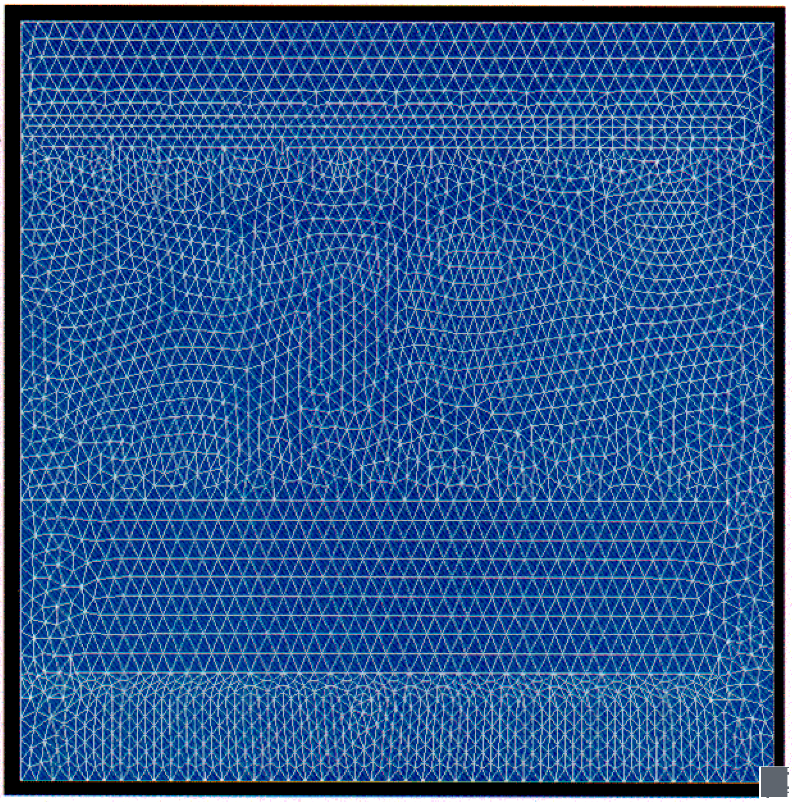

Figure C-3. Finite element mesh used in the HYDRUS 2D simulation of the CFA-08 drainfield.

Table C-2. Material properties used in the HYDRUS 2D simulation.

Lithologic Unit	Residual Moisture Content	Saturated Moisture Content	van Genuchten α (1/m)	van Genuchten n	Saturated Hydraulic Conductivity (m/d)
Silt loam	0.067	0.45	2	1.41	0.108
Basalt	0.001	0.05	10	2.5	0.25

The simulation was run until moisture contents in the unsaturated zone equilibrated (30 yr). A second simulation was then constructed using the moisture contents at the end of the first simulation as initial conditions and modifying the top boundary conditions such that a background infiltration of 1 cm/yr was assigned to the entire top boundary. This simulation was run for another 30 yr and provided both water and solute fluxes to the aquifer during the drain-out period after cessation of drainfield operations in 1995.

C4. DRAINFIELD WATER EFFLUENT FLOW RATE

Information regarding liquid effluent discharge rates to the drainfield were originally provided by C. Craiglow[a] and included the design maximum flow rate (1,325,000 L/d), maximum recorded flow rate (757,000 L/d), summer average flow rate (662,000 L/day), and winter average flow rate (416,400L/day).

a. Personal communication from Carol Craiglow, Bechtel BWXT Idaho, LLC, (BBWI) scientist, to Arthur Rood, BBWI advisory scientist, November 9 and 30,1999.

Nitrate concentrations in the effluent were estimated to be between –30 and 70 mg/L. The original simulation used the water flux and solute concentration as calibration parameters. Calibrated values for these parameters were 260,000 m^3/yr (712,330 L/d) and 61.5 mg/L for the liquid effluent flow rate and solute concentration, respectively. The water flux was used in this simulation without modification. Solute concentrations were adjusted to provide a qualitative match between observations and model predictions.

C5. GWSCREEN MODEL INPUT

A summary of model input parameters for GWSCREEN is provided in Table C-3 and taken largely from the original assessment (INEEL 2002). Parameters that require additional justification are discussed below.

Table C-3. GWSCREEN model parameters and values used in the simulation.

Parameter Name	Value	Reference or Justification
Source length (m)	305	Personal communication with C. Craiglow"
Source width (m)	61	Personal communication with C. Craiglow"
Operation time of drainfield (yr)	42	Personal communication with C. Craiglow"
Aquifer thickness (m)	76	DOE-ID 1994
Aquifer bulk density (g cm^{-3})	1.9	DOE-ID 1994
Aquifer porosity	0.06	Magnuson and Sondrup 1998
Aquifer Darcy velocity (m yr^{-1})	15 to 30	Estimated from the OU-3-13 remedial investigatiodfeasibility study model
Longitudinal dispersivity	Variable	See discussion
Transverse/longitudinal ratio	0.8	Calibrated value- see discussion
Vertical/longitudinal ratio	0.001	Calibrated value from original assessment – see discussion
Groundwater flow direction (azimuth)	198°	Calibrated value – see discussion
Longitudinal distance to CFA-MON-1 well (m)	2649	Calculated based on universal transverse mercator (UTM) map coordinates and direction of groundwater flow
Transverse distance to CFA-MON-1 well (m)	621	Calculated based on UTM map coordinates and direction of groundwater flow
Longitudinal distance to CFA-MON-2 well (m)	2475	Calculated based on UTM map coordinates and direction of groundwater flow
Transverse distance to CFA-MON-2 well (m)	133	Calculated based on UTM map coordinates and direction of groundwater flow
Longitudinal distance to CFA-MON-3 well (m)	2341	Calculated based on UTM map coordinates and direction of groundwater flow
Transverse distance to CFA-MON-3 well (m)	306	Calculated based on UTM map coordinates and direction of groundwater flow
Nitrate concentration (mg/L)	Variable	Several scenarios are presented

a. Data provided by Carol Craiglow, BBWI scientist, were derived from previous analysis, published and unpublished reports, and assumptions.

C6. DIRECTION OF GROUNDWATER FLOW AND DISPERSIVITY

The general direction of groundwater flow in the CFA vicinity is from north to south (180" azimuth). Assuming the source of nitrate measured in the CFA-MON-A-001 through -003 wells originated from the CFA-08 drainfield, the direction of groundwater flow would have to be slightly more than 180° to achieve the observed distribution of concentrations in the wells. Originally, the water table contour map provided in nitrate evaluation (INEEL 2002) indicated this was a reasonable assumption and showed the mean direction of groundwater flow to be about **S** 10"W. However, recent water table contour maps in the vicinity of CFA show the direction of flow to be trending southeast. If such is the case, then it would be difficult to envision CFA-08 as the source of the observed nitrate in the CFA monitoring wells.

For these calculations, it was assumed that the nitrate observed in the CFA monitoring wells originated from CFA-08. The direction of groundwater flow was then adjusted to get the correct distribution of nitrate concentrations in each of the wells. Measured nitrate concentrations (Table C-1) were time-averaged and normalized to the time-averaged concentration in CFA-MON-A-002. These normalized concentrations were then compared to normalized predicted concentrations. By adjusting the mean direction of groundwater flow and transverse dispersivity, the predicted normalized concentrations between the three wells could be matched to the observed normalized concentrations. Solute concentrations in the effluent could then be adjusted to match the absolute concentrations in the wells.

Using the procedure defined above, the mean groundwater flow direction had an azimuth of 198" **(S** 18"W). Because dispersivity is a scale-dependent phenomenon, larger model domains typically require larger values for dispersivity. The scale-dependent nature of dispersivity has been incorporated into the GWSCREEN Version 2.5 model. Instead of using a fixed value for longitudinal dispersivity for all receptors in the model domain, the longitudinal dispersivity is allowed to vary as a function of receptor distance and is given by:

$$\alpha_L = 0.83(\log_{10} L)^{2.414} \tag{C-1}$$

where

α_L = the longitudinal dispersivity (m)

L = the receptor distance (m).

Using Equation (C-1) and a receptor located on the downgradient edge of the source (152 m downgradient from the source center) yields a value for α_L of 5.5 m. The transverse and vertical dispersivity are some fraction of the longitudinal dispersivity. The calibration procedure defined above yielded a ratio of the transverse to longitudinal dispersivity of 0.8. The ratio of the vertical to longitudinal dispersivity used in the original assessment (0.001) was retained.

C7. DARCY VELOCITY

Based on the OU 3-13 remedial investigatiodfeasibility study, the original assessment used a Darcy velocity of 30 m/yr. This value, while credible for an overall average value, could be substantially different depending on local-scale heterogeneity. Darcy velocity can be important in terms of the amount of dilution that occurs and in transit times in the aquifer. The 30-m/yr value resulted in transit times from CFA-08 to the CFA monitoring wells of about 5 yr. If the nitrate in the CFA monitoring wells originated from the CFA-08 drainfield, then the mean Darcy velocity between the drainfield and the monitoring wells is expected to be lower, because the drainfield ceased operation in 1995, yet nitrate concentrations in the monitoring wells persist to the present day. Therefore, a lower Darcy velocity in the aquifer might be expected. Lower Darcy velocities in the aquifer also result in less dilution of nitrate-contaminated water entering the aquifer. The original model required a nitrate concentration of 61.5 mg/L to achieve the observed concentrations in the CFA monitoring wells. This value was well above the upper end of estimated nitrate concentrations in the effluent released to the drainfield. A more credible value might be in the 20- to 30-mg/L range.

C8. INCORPORATION OF WATER AND SOLUTE FLUXES FROM HYDRUS INTO GWSCREEN

The conceptual model employed in GWSCREEN assumes the aquifer is contained within a homogenous isotropic porous media of infinite lateral extent and finite thickness with no water sources or sinks. Under background infiltration conditions, the amount of water entering the aquifer is negligible compared to the flow in the aquifer. However, in the case of the drainfield, a significant amount of water enters the aquifer. This water can affect both aquifer flow and solute concentrations in the vicinity of the source. At further distances from the source, the effects of the drainfield on solute concentrations and water flow are diminished.

GWSCREEN uses a spatially dependent dilution factor to account for additional water entering the aquifer from the infiltration source, such as the drainfield or percolation pond. However, the dilution calculation in GWSCREEN is only applied to a steady-state water flux entering the aquifer. Because the water flux calculated with HYDRUS changes as a function of time, the dilution factor had to be calculated for outside the code. The dilution factor is given by:

$$DF = \frac{(\sigma_y + W)b_x q}{(\sigma_y + W)b_x q + q_a} \qquad \text{(C-2)}$$

where

DF	=	the dilution factor
σ_y	=	the standard deviation of the plume in the transverse direction (m)
W	=	the width of the source perpendicular to groundwater flow (m)
b_x	=	vertical mixing term (m)
q	=	Darcy velocity in aquifer (m/y)
q_a	=	Darcy velocity in unsaturated zone from operation of the facility (dyr).

The standard deviation of the plume in the transverse (σ_y) and vertical (σ_z) direction is given by:

$$\sigma_y = \sqrt{\frac{2\alpha_T x}{R_d}} \qquad \sigma_z = \sqrt{\frac{2\alpha_V x}{R_d}} \qquad \text{(C-3)}$$

where

α_T	=	transverse dispersivity (m)
α_V	=	vertical dispersivity (m)
x	–	distance to receptor parallel groundwater flow (m)
R_d	=	retardation coefficient (1.0 for nitrate).

The vertical term *(b,)* for the three-dimensional vertically-averaged solution is given by σ_z when $\sigma_z > b$, where b is the averaging thickness (6.1 m based on the well screen thickness).

Values for the dilution factor were calculated separately for each monitoring well and each output time and were multiplied by the corresponding GWSCREEN aquifer concentration to yield a corrected concentration in the aquifer. HYDRUS-calculated water fluxes to the aquifer (q_a) were scaled to the estimated water flux to the *entire* drainfield.

C9. NITRATE MODELING RESULTS

HYDRUS-calculated water and solute fluxes (for a unit [1 mol/m^3] nitrate concentration) to the aquifer during and after drainfield operation (see Figure C-4) show that the unsaturated zone wets up rapidly and achieves a steady state in a short time and were reasonably well approximated by the GWSCREEN pond model. After operations ceased in 1995, solute and water fluxes decline over time.

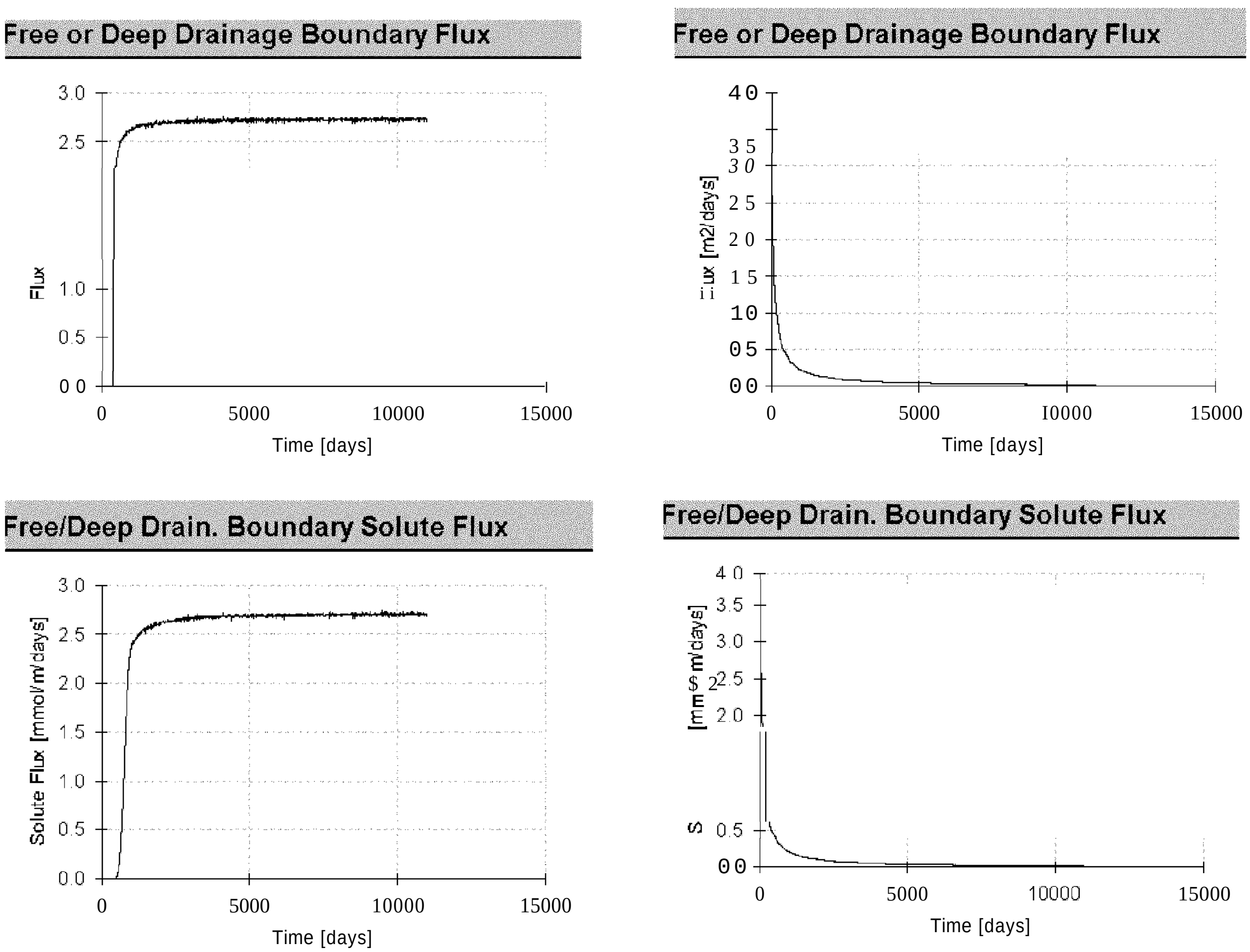

Figure C-4. Water and solute fluxes to the aquifer, as calculated by HYDRUS for a unit (1 mol/m^3) concentration in the drainfield effluent. The frames on the left show the buildup over time of the water and solute flux. Time in these frames is the time from the start of operations (i.e., 1953). The frames on the right show the water and solute flux during the drain-out period after operation of the drainfield ceased in 1995. The time in these frames is the time from 1995.

Predicted nitrate concentrations in the CFA monitoring wells as a function of time were evaluated for Darcy velocities of 25 m/yr and 12.5 m/yr (see Figures C-5 and C-6). Nitrate effluent concentrations were adjusted to match the predicted concentration with the observed values. A 50-mg/L nitrate effluent concentration yielded aquifer concentrations in the CFA monitoring wells consistent with observations for a 25-m/yr Darcy velocity. Likewise, a 25-mg/L nitrate effluent concentration yielded aquifer concentrations in the CFA monitoring wells consistent with observations for a 12.5-m/yr Darcy velocity in the aquifer.

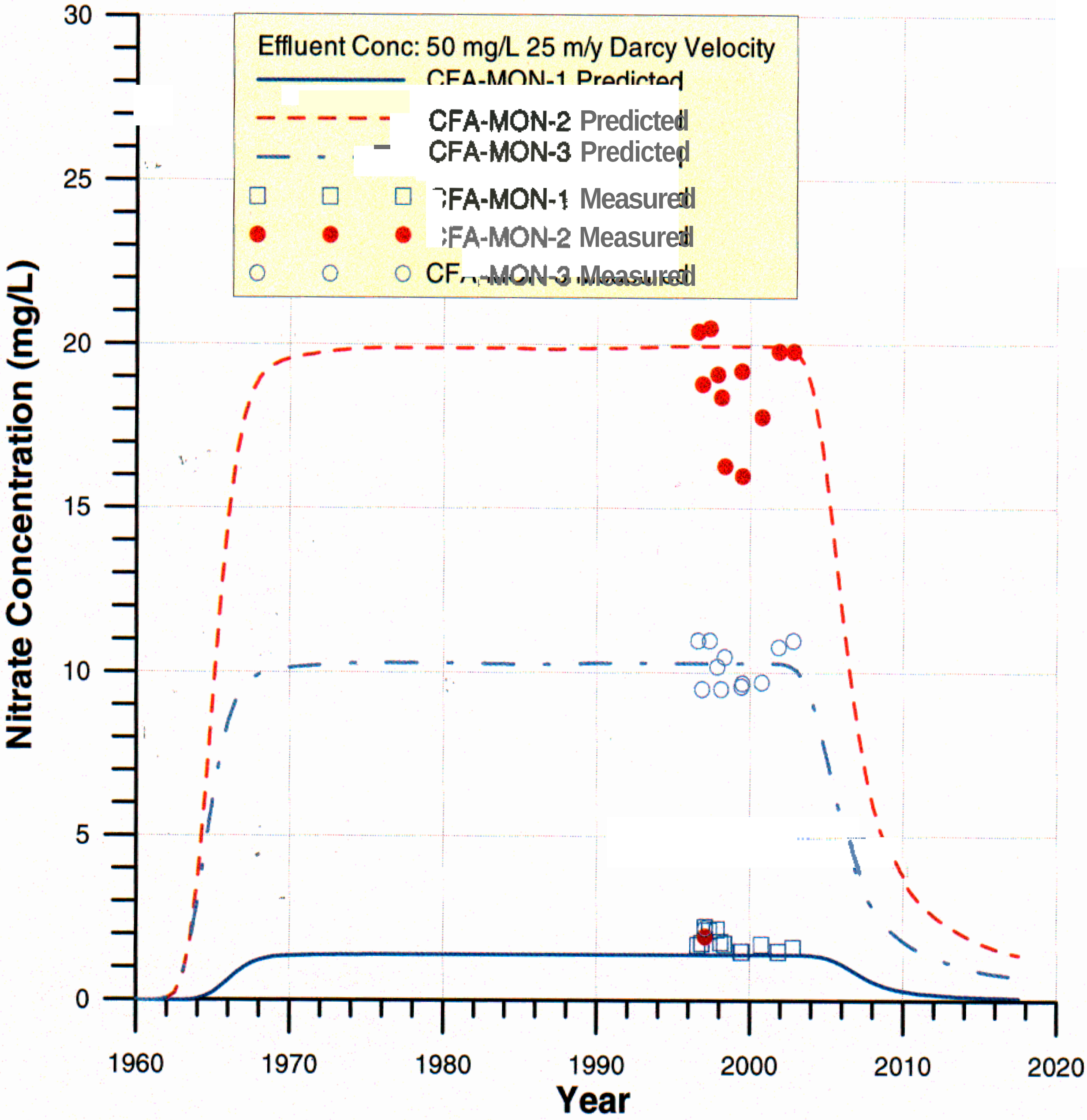

Figure C-5. predicted and observed nitrate concentrations in CFA monitoring wells as a function of time for 25-m/yr Darcy velocity in the aquifer and 50-mg/L nitrate effluent concentration.

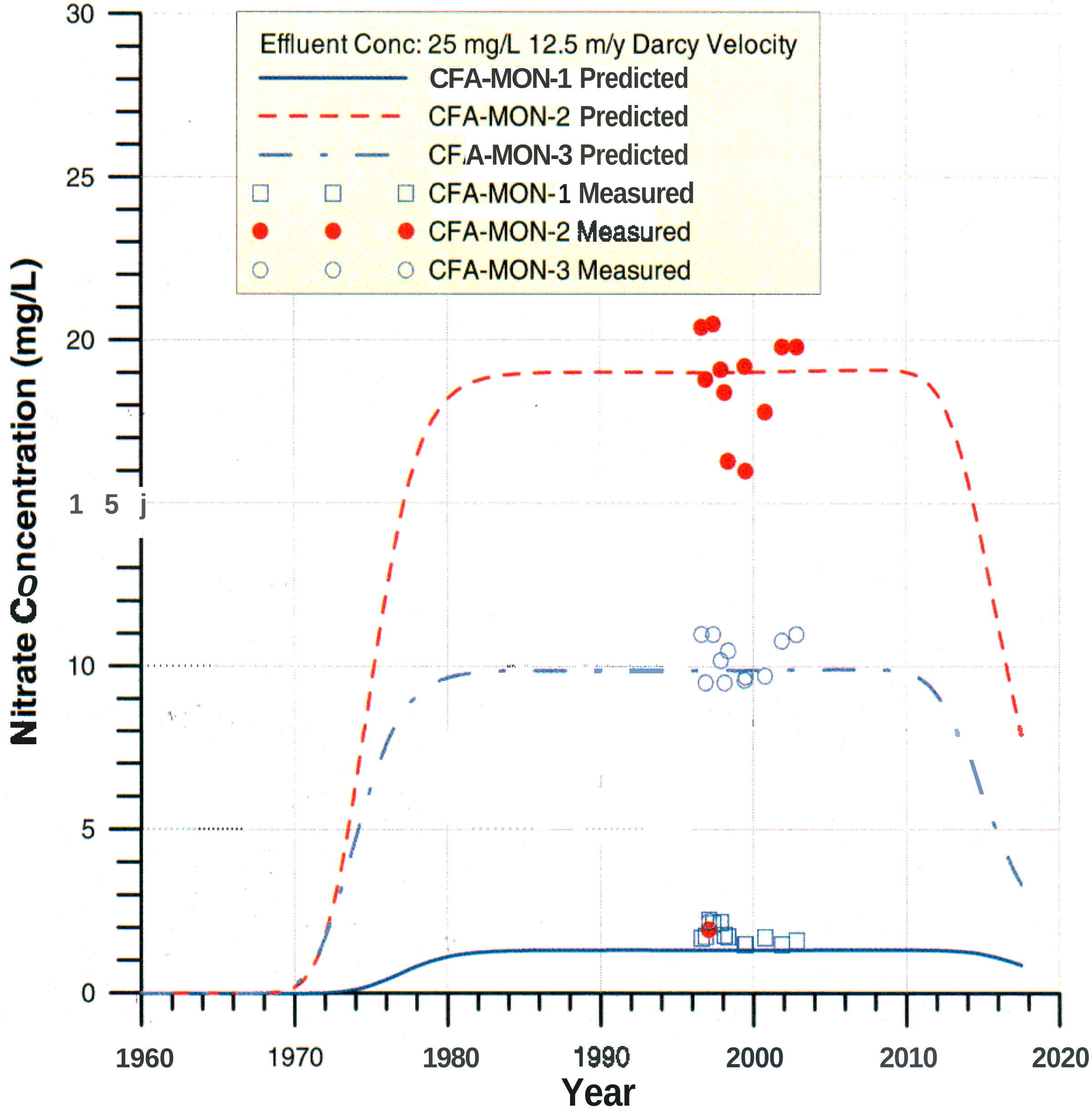

Figure C-6. Predicted and observed nitrate concentrations in CFA monitoring wells as a function of time for 12.5-m/yr Darcy velocity in the aquifer and 25-mg/L nitrate effluent concentration.

C10. CHLORIDE MODELING RESULTS

Chloride was also present in the drainfield effluent at elevated concentrations and is associated with the nitrate in CFA-MON-A-002 and -003. Neither chloride nor nitrate sorb or decay in oxygenated groundwater and therefore move at the same rate. Chloride concentrations in the CFA monitoring wells were calculated by scaling the predicted nitrate concentrations by the average chloride effluent concentration of 222 mg/L from 1988 to 1994. The chloride concentration was probably much lower than 222 mg/L during the initial years of operation, because the CFA production wells were not affected by the chloride plume at the Idaho Nuclear Technology and Engineering Center (INTEC). By 1968, however, the INTEC chloride plume affected CFA-2, but the exact timing of influence from the INTEC chloride plume is unknown because of a data gap from 1956 to 1968.

Using the scaling procedure described above and an average 222-mg/L chloride concentration, the predicted concentrations of chloride in the CFA monitoring wells were compared with measurements (see Figures C-7 and *C-8)*. In all wells, predicted chloride concentrations exceeded corresponding measured values without considering that chloride concentrations were near 90 mg/L in wells *upgradient* of CFA-OS. The chloride detected in the upgradient wells presumably originated from INTEC. Dilution and dispersion could reduce the upgradient concentration (90 mg/L) to *~50* mg/L at the CFA monitoring wells, which would account for most of the chloride observed in the wells. It is therefore possible *that* most of the chloride observed in the CFA monitoring wells originates from INTEC sources and not from CFA-OS. This observation suggests that the groundwater flow direction of S 18° W used in this assessment is incorrect. Instead, the direction may be closer to what recent water head elevation maps suggest, which was slightly east of true south. If such is the case, then most of the nitrate and chloride released from the drainfield would not have been detected in the monitoring wells.

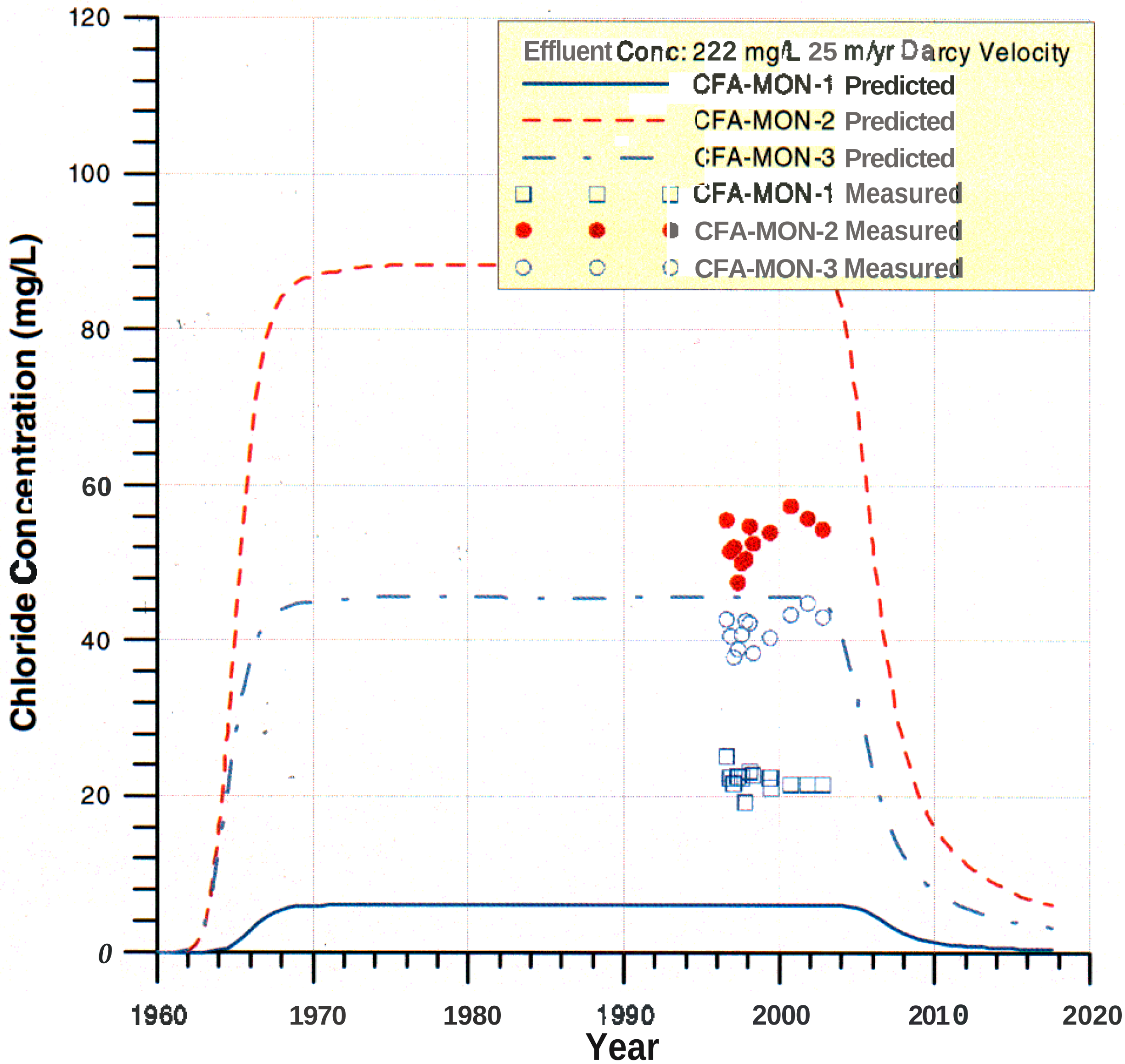

Figure C-7. Predicted and measured chloride concentrations in CFA monitoring wells as a function of time for 25-m/yr Darcy velocity in the aquifer and 222-mg/L chloride effluent concentration.

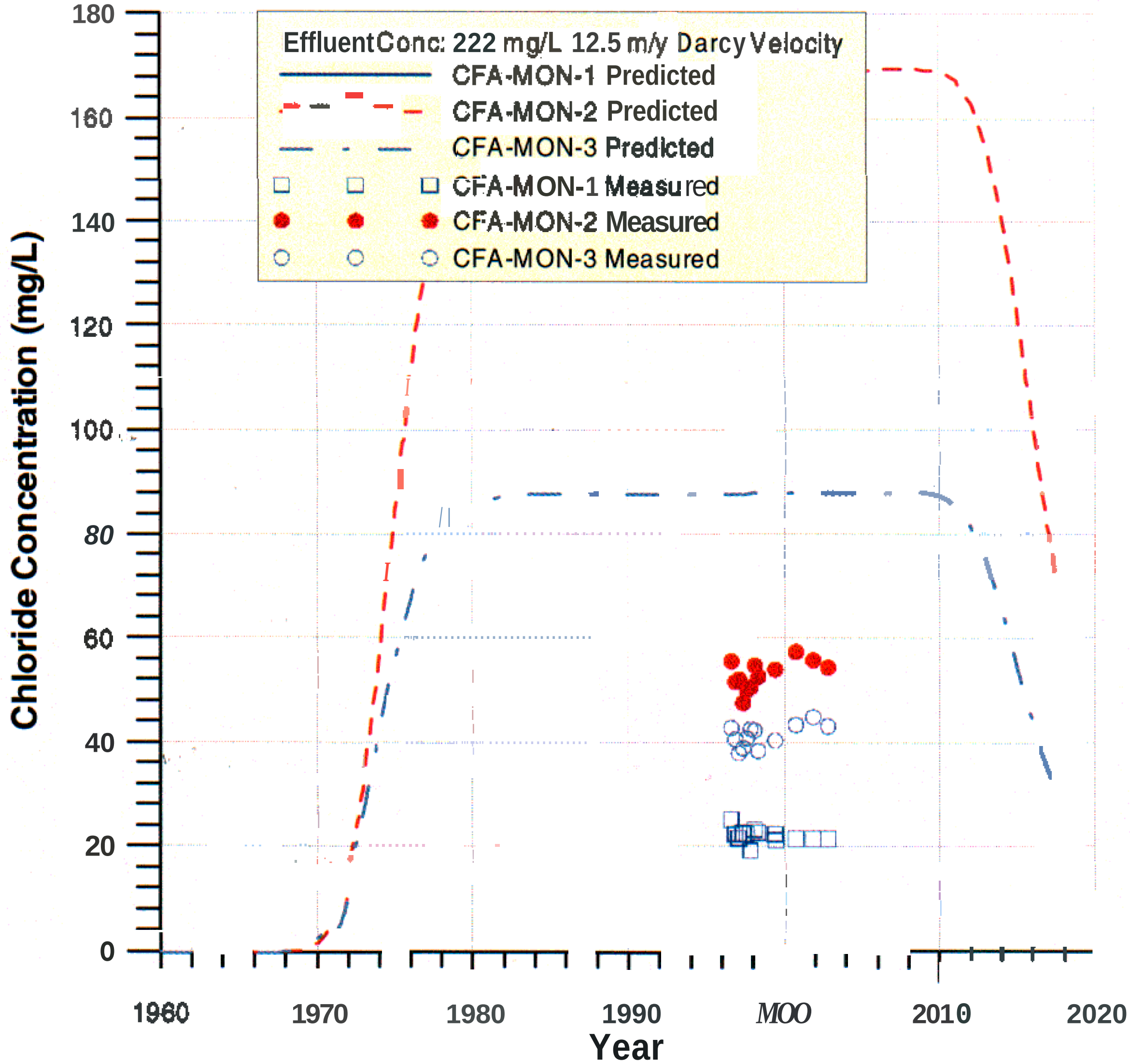

Figure C-8. Predicted chloride concentrations in CFA monitoring wells as a function of time for 12.5-m/yr Darcy velocity in the aquifer and 222-mg/L chloride effluent concentration.

C11. CONCLUSIONS

The analysis suggests *that* it is possible for the CFA-08 drainfield to be the source of the nitrate observed in the CFA monitoring wells. But it does not seem plausible that the chloride concentration observed in the monitoring wells could have originated from CFA-08. Both chloride and nitrate were detected in the drainfield effluent, so one would likely be detected with the other at different wells and at the same relative concentration. However, the chloride/nitrate ratios in the effluent do not match the chloride/nitrate ratios in the monitoring wells. Additionally, recent water head elevation maps indicate a mean direction of groundwater flow trending southeast instead of S 18° W, which was the direction assumed for this assessment. If such is the *case*, then it would be difficult for the CFA-08 drainfield to be a credible source of the nitrate observed in the CFA monitoring wells, because the direction of the flow would take the plume away from the monitoring wells. Taken together, the evidence suggests that CFA-08 is not the source of nitrate observed in the CFA monitoring wells and that *other* potential sources (such as CFA-04) should be investigated.

C12. REFERENCES

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